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A Monte Carlo study of B_s^0 and B_d^0 initial state tagging

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1 Introduction

Measurement of time-dependent B–$\overline{\text{B}}$ mixing requires the identification, "tagging", of the initial and final states of the B. To this end we have investigated and compared various methods of tagging the initial state of the B using the charged tracks in the event that do not come from the B–meson.

Results on tagging of B(= B_s^0 ,B_d^0) for 54032 1991 $b\bar{b}$ Monte Carlo events are presented. For each event, the MC truth B_s^0 and B_d^0 mesons are found. The event is divided into two hemispheres using the thrust axis calculated from the reconstructed tracks. The tags are then calculated using the reconstructed tracks excluding the reconstructed daughters of the B if the tag is created from tracks in the same hemisphere as the B. The reconstruction of exclusive and semi–exclusive B will not be discussed in this note.

In all cases the sign of the tagger is used to predict the initial state of the B. 'Good' tags result when the initial state is correctly predicted. We define

- F(good) $\equiv$ (Number of B correctly tagged) / (Number of B with tag available),
- $\eta \equiv 1-$F(good) = mistag fraction,
- $\epsilon \equiv$ efficiency = (Number of B with tag available)/ (Total number of B), and
- $\psi \equiv \epsilon(1-2\eta)^2$ = relative quality factor [1].

2 Definitions and descriptions of the tags

The power and utility of a tag formed using a high p_T lepton in the hemisphere opposite to the B has been amply demonstrated [3, 4]. The tag used in this study is defined below

- LepTag $\equiv$ 'standard' leptons with $p > 3$ GeV and $p_T > 1$ GeV calculated as described in ALEPH 92-101[2]. Briefly: jets are calculated from Energy flow objects with the lepton included with $Y_{cut} = (6.0/QELEP)^2$. The p_T is calculated with respect to the jet with the lepton removed. The effect of $p_T > 1.25$ GeV has also been studied.

The use of the jet charge, Q_{JET}, in the hemisphere opposite to the B has already been described [1] and has a relatively long history [5]. It is defined as follows, where the sum extends over all "good" tracks in the opposite(same) hemisphere as the B (excluding the tracks coming from the B):

$$Q_{JET} \equiv \frac{\sum_i |\vec{p_i} \cdot \vec{T}|^{\kappa} \times q_i}{\sum_i |\vec{p_i} \cdot \vec{T}|^{\kappa}}$$

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where

- $\vec{p_i}$ = momentum of the i^{th} track,
- $\vec{\mathrm{T}}$ = thrust unit vector,
- q_i = charge of the i^{th} track, and
- $\kappa = 0.5$ according to [6].

Since it uses all the available "good" tracks in the event, $\mathrm{Q_{JET}}$ is very efficient.

It was recognized that since an s–quark is expected to be co–produced with the $\mathrm{B_s^0}$, a charged kaon could provide a method to identify the initial state of the $\mathrm{B_s^0}$ [7]. Although this type of tag will naturally have a lower efficiency than $\mathrm{Q_{JET}}$ because of the co–production of neutral kaons or baryons, it has the potential to discriminate against $\mathrm{B_d^0}$ contamination in the case of semi–exclusive $\mathrm{B_s^0}$ reconstruction. For example, in the case of $\mathrm{B_s^0} \rightarrow \mathrm{D_s}$ + hadrons reconstruction [1], the use of kaon tagging could reduce the contribution from $\mathrm{B_d^0} \rightarrow \mathrm{D_s}$ X. This $\mathrm{K_{TAG}}$ is defined below where an additional "tag" that does not require kaon identification is also defined for comparative purposes.

- $\mathrm{K_{TAG}}$ = the highest momentum track positively identified as a kaon, $|\chi_K| \leq 2.0$, coming from the primary vertex in a 45° cone around the B,[8]
- Fastag = highest momentum track in a 45° cone around the B,

A final set of additional tags was studied in an attempt to exploit the high efficiency of $\mathrm{Q_{JET}}$(same) and the power of the $\mathrm{K_{TAG}}$. The "flavor–weighted jet charge", $\mathrm{Q_{JET}^F}$, is defined below, where the sum over i extends over all "good" tracks in the same hemisphere as the B and excludes the tracks coming from the B.

$$\mathrm{Q_{JET}^{\mathit{a}}} \equiv \frac{\sum_j^3 \sum_i |\vec{p_i} \cdot \vec{\mathrm{T}}|^\kappa q_i f_{ij}}{\sum_j^3 \sum_i |\vec{p_i} \cdot \vec{\mathrm{T}}|^\kappa |f_{ij}|}$$

where

- $j = 1, 2, 3 = \pi, K, p$,
- $f_{ij} = g_{ij} \times s_j$
- $s_j = 0.4, 1.0, 0.25$ for $a = \mathrm{F}$,
- $s_j = 1.0, 0.0, 0.00$ for $a = \pi$,
- $s_j = 0.0, 1.0, 0.00$ for $a = K$,
- $s_j = 0.0, 0.0, 1.00$ for $a = p$,
- $s_j = 0.4, 1.0, 0.00[0.25]$ for $a = \mathrm{F(NSP)}$ and $p_i \leq [>]$ 2.5 GeV/c, "NSP" ≡ "No Slow Protons", and
- $g_{ij} = g_{ij}(z_i)$ = probability that track i with fractional momentum, $z_i \equiv p_i/p_{\text{beam}}$, is type $j = \pi, K, p$ according to the measured particle fractions shown in Figure 1[9] and the measured dE/dx ionization(if available).

Explicitly, (this is essentially equation (3) of reference [9]),

$$g_{ij} = Cr_j(z_i) \times \frac{1}{\sqrt{2\pi}\sigma_{ij}} \exp\left(\frac{(\mathrm{I}_i^{meas} - \mathrm{I}_{ij}^{exp})^2}{2\sigma_{ij}^2}\right).$$

where

- C = a normalization factor such that $\sum_j g_{ij} = 1$,
- $r_j(z_i)$ = the measured particle fractions shown in Figure 1,
- I_i^{meas} = the measured dE/dx ionization of track i,
- I_{ij}^{exp} = the expected dE/dx ionization of track i for hypothesis $j = \pi, K, p$, and
- σ_{ij} = the calculated resolution on I_{ij}^{exp}.

In the case where the dE/dx information is not available, $g_{ij} = Cr_j(z_i)$.

The values of $s_j = 0.4, 1.0, 0.25$ have been chosen to optimize the response of Q_{JET}^{F} and $Q_{JET}^{F(NSP)}$ for B_s^0 –tagging. The 2.5 GeV/c cutoff was chosen to exclude the region where proton production from nuclear interactions is appreciable [9].

3 Discussion

It is evident that despite the good agreement of the Monte Carlo with the measured charged hadron production in ALEPH and other experiments [9], the following results are model dependent. Methods to verify these results using the data are currently under development.

Figure 2 shows the calculated jet charge distributions for B_s^0 and B_d^0 . As shown in Tables 1 and 2, there is good agreement in F(good) between the opposite side tags, Q_{JET}(oppo) and LepTag, for B_s^0 and B_d^0 as expected.

As surmised, with the exploitation of the flavor correlation, K_{TAG} is more effective at tagging B_s^0 than B_d^0 , F(B_s^0) = 66.5±0.5% and F(B_d^0) = 56.8±0.3% and ψ(B_s^0) = 0.065 ± 0.004 and ψ(B_d^0) = 0.011 ± 0.001, but only marginally more effective than Fastag in tagging the initial B_s^0 due to the much higher efficiency of Fastag since dE/dx information is not required. The performance of $K_{TAG}$and Q_{JET}(same) is also in good agreement with results for semi–exclusive B_s^0 –reconstruction to D_s^+, l^- as shown in Table 3. [10]

Comparison of Fastag and Q_{JET}(same) show that both are significantly ($> 4\sigma$) more effective in B_s^0 – than B_d^0 –tagging. The slight difference for B_s^0 and B_d^0 events in Q_{JET}(same) can also be seen in Figure 2. A possible explanation is that the average momentum of a kaon from a K^* that is co–produced with a B_s^0 will be slightly higher than a pion from a ρ that is co–produced with a B_d^0 .

As seen in Table 1, the optimized Q_{JET}^{F} shows a significant improvement over Q_{JET}(same) — the relative error in the difference between the two is negligible since all the events are shared — as does $Q_{JET}^{F(NSP)}$which attains a tagging fraction comparable to K_{TAG} and an improvement in the relative quality factor of more than 15% over Q_{JET}(same). The optimization of the s_j for B_s^0 –tagging was performed over the ranges $0 \leq s_\pi \leq 2$ and $-2 \leq s_p \leq 4$ with s_K fixed at unity. With perfect hadron identification, one would expect $s_\pi \ll s_K$ and $s_p \approx -s_K$ since protons from co–produced Λ are oppositely signed with respect to the co–produced charged kaons; however, in the real world (or, at least, in ALEPH's perception of the world), protons and kaons are not so easily separated so $s_K > s_\pi \geq s_p$.

The sensitivity of Q_{JET}^{F} and $Q_{JET}^{F(NSP)}$ to the measured particle fractions was tested by assuming equal fractions of pions, kaons and protons at all values of z_i. The resulting flavor–weighted jet charges are listed as $Q_{JET}^{F}(1/3)$ and $Q_{JET}^{F(NSP)}(1/3)$ in the tables. Despite the expected reduction in the tagging fractions and subsequent loss in the quality factors, $\psi(Q_{JET}^{F(NSP)})$ and $\psi(Q_{JET}^{F})$ still show an improvement over Q_{JET}(same).

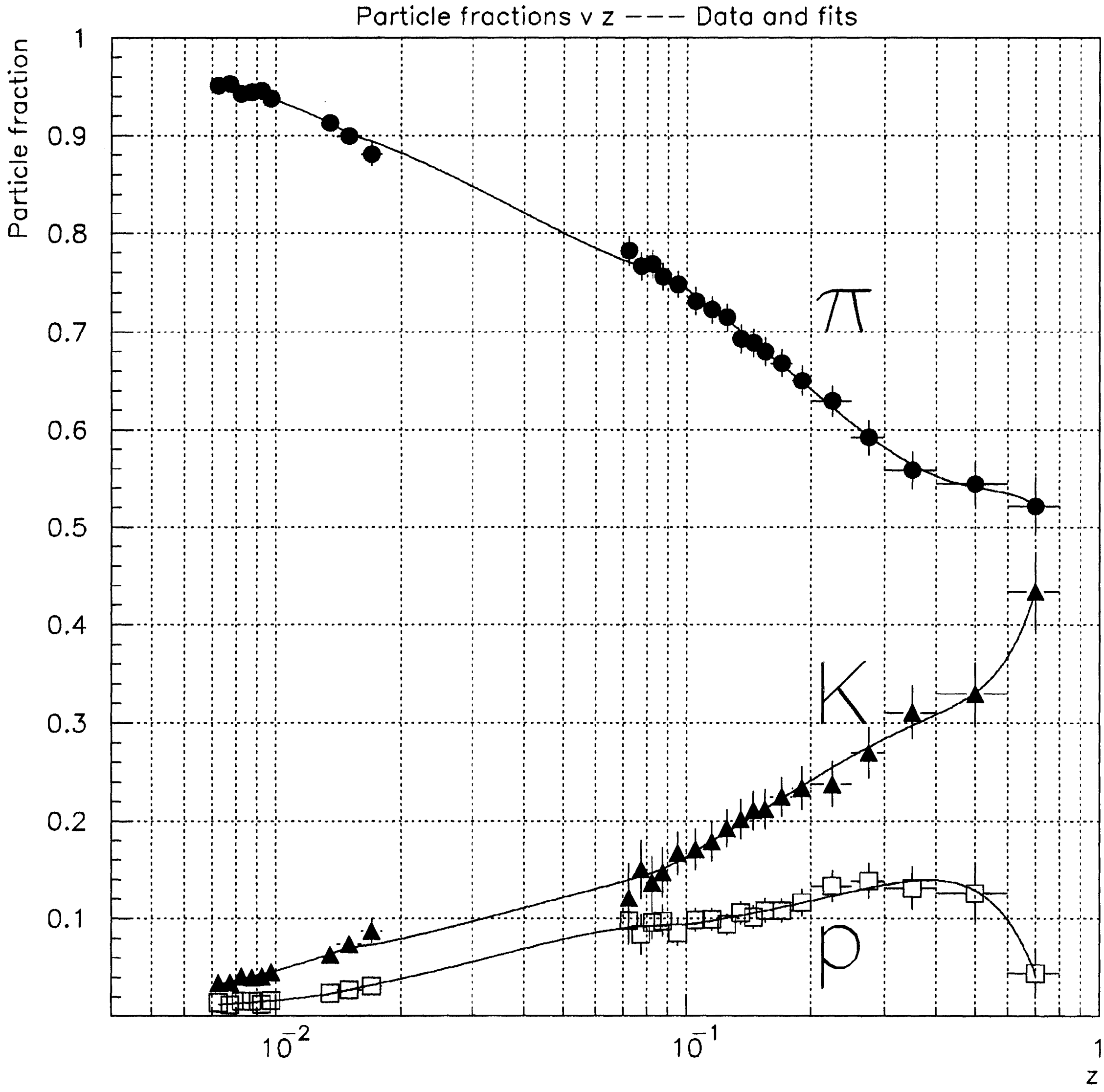

Figure 1: Measured charged pion, kaon and proton fractions with fit

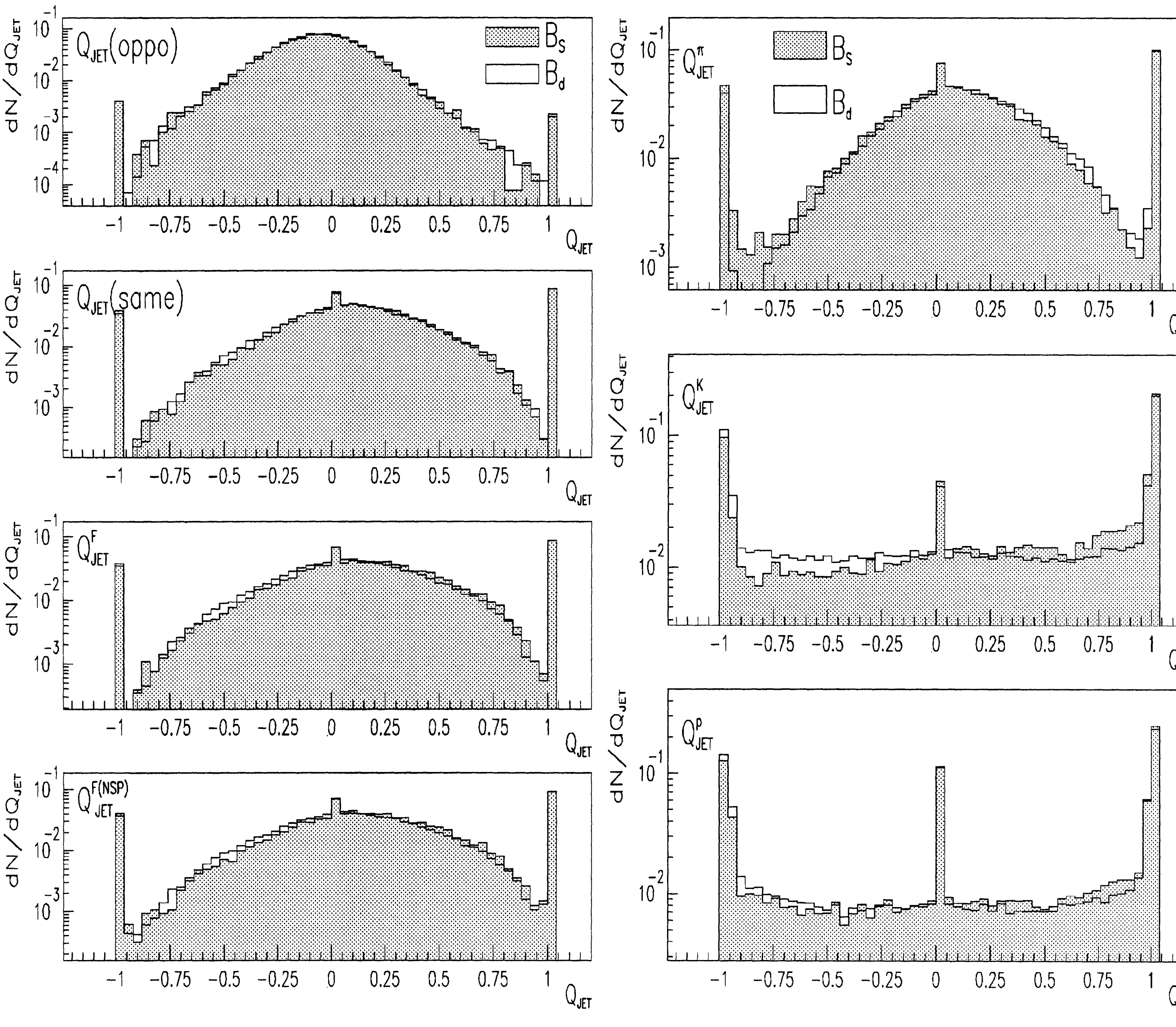

Figure 2: Jet charge distributions for Bs and Bd events. The integrals of the distributions have been normalized to unity.Q_{JET} is exactly zero when there are no "good" tracks in the hemisphere. Note the vertical logarithmic scale

4 Momentum dependence of tagging

The X(B)–dependence of the same side tags is presented in Figure 3 and 4 for B_s^0 – and B_d^0 – tagging, respectively. The ability to correctly tag the initial state of the B increases monotonically with X(B) for all the same–hemisphere tags.

Figure 5 shows the B_s^0 – and B_d^0 –tagging dependence of the opposite hemisphere tags, Q_{JET} and LepTag, on X(B). The high p_T lepton tag ($p_T > 1.\text{GeV}/c$) shows no dependence on X(B) as expected. Linear fits of the form $(1-\eta) = a_0 + a_1 X(B)$ for Q_{JET} yield $a_0 = 0.606 \pm 0.015 (0.618 \pm 0.008)$ and $a_1 = 0.066 \pm 0.021 (0.036 \pm 0.021)$ for B_s^0 (B_d^0) showing a marginally significant dependence of X(B). At low X(B) the thrust direction may be relatively poorly defined, thus there could be some hemisphere swapping of some tracks which would increase the mistagging fraction.

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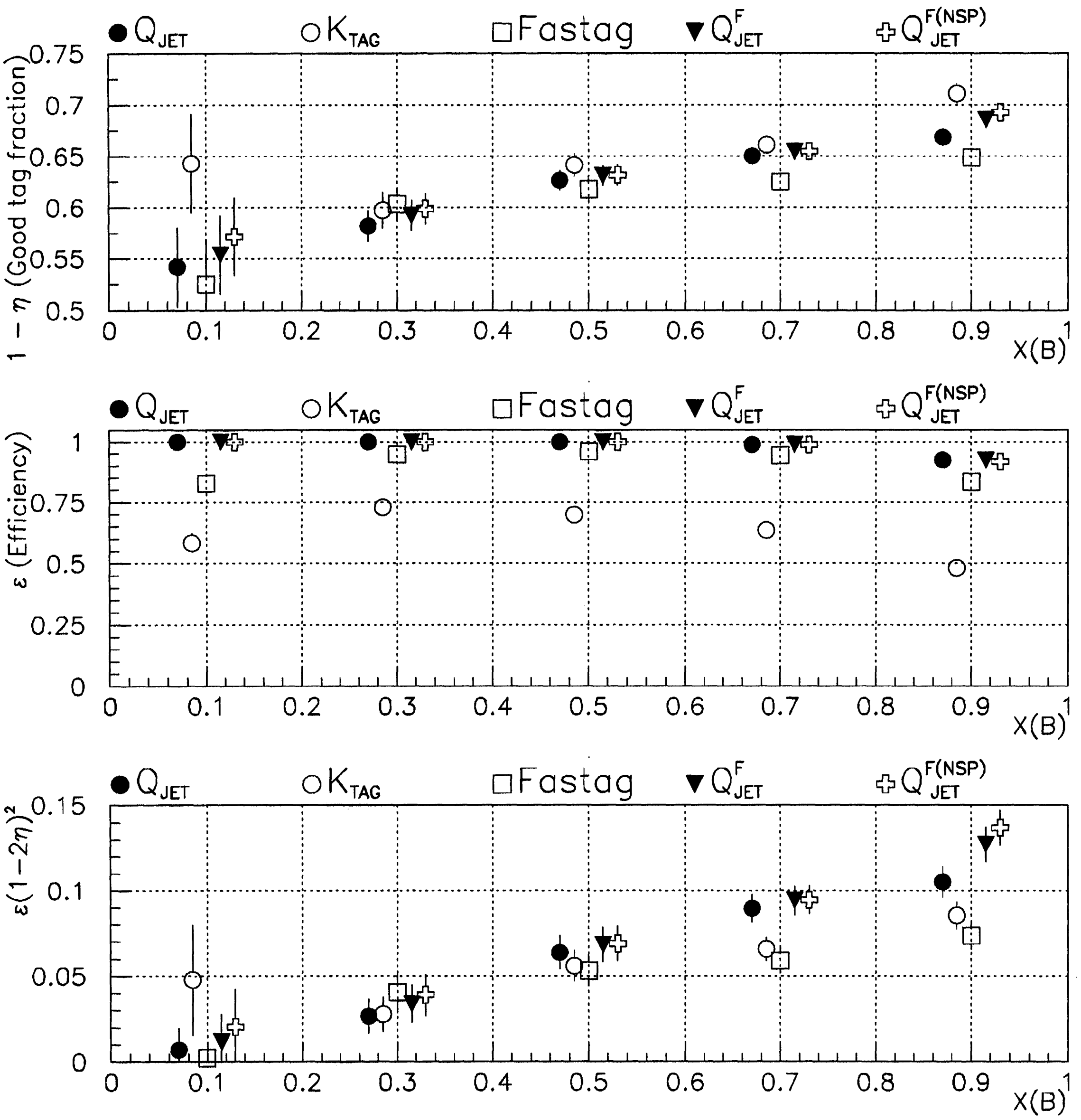

Figure 3: The tagging fraction, efficiency and relative quality factors for various B_s^0 –tags using tracks in the same hemisphere as a function of X(B). Note the suppressed zeros. The points are offset from the bin centers to make them easier to see.

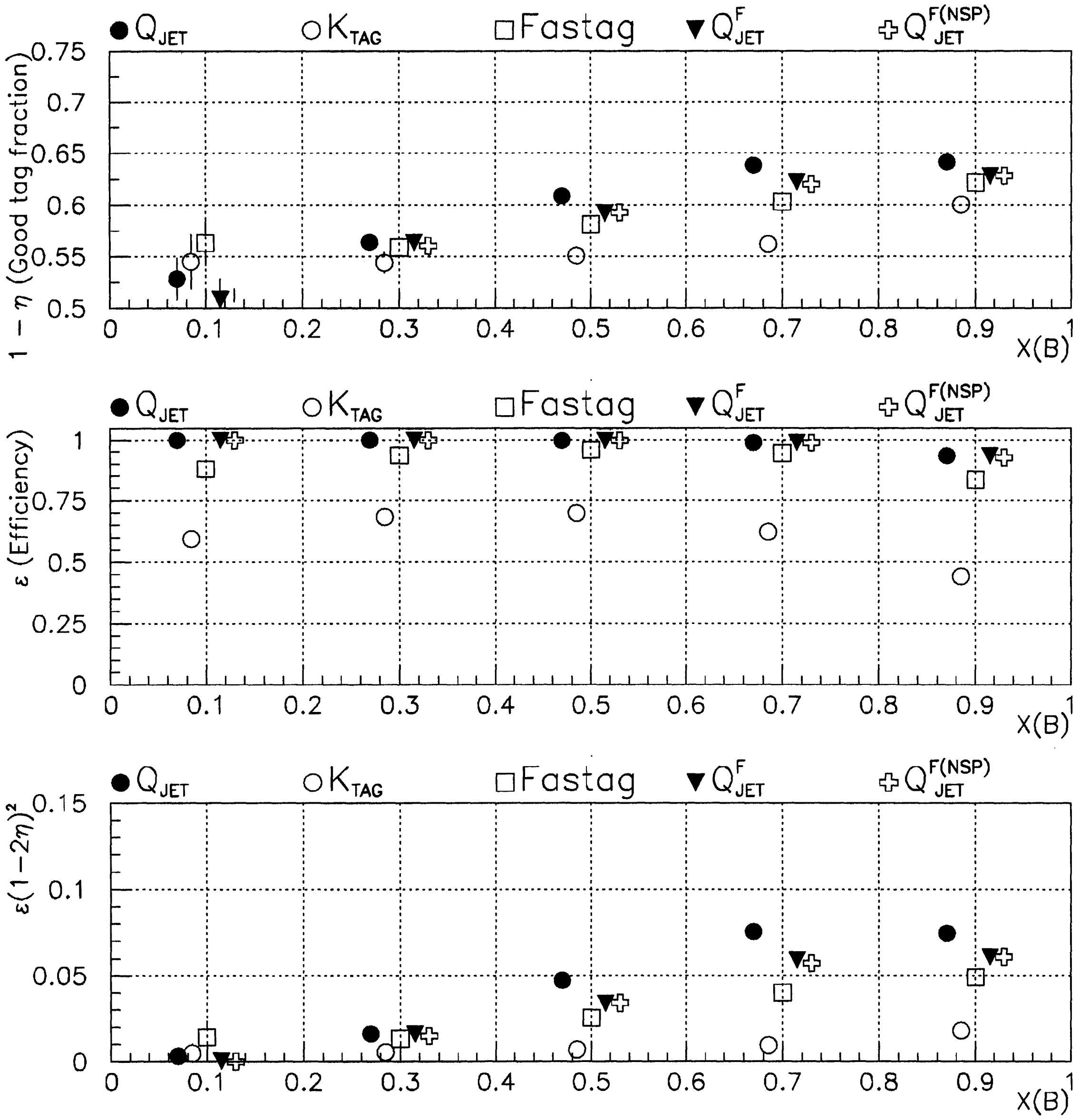

Figure 4: The tagging fraction, efficiency and relative quality factors for various B_d^0 –tags using tracks in the same hemisphere as a function of X(B). Note the suppressed zeros.The points are offset from the bin centers to make them easier to see.

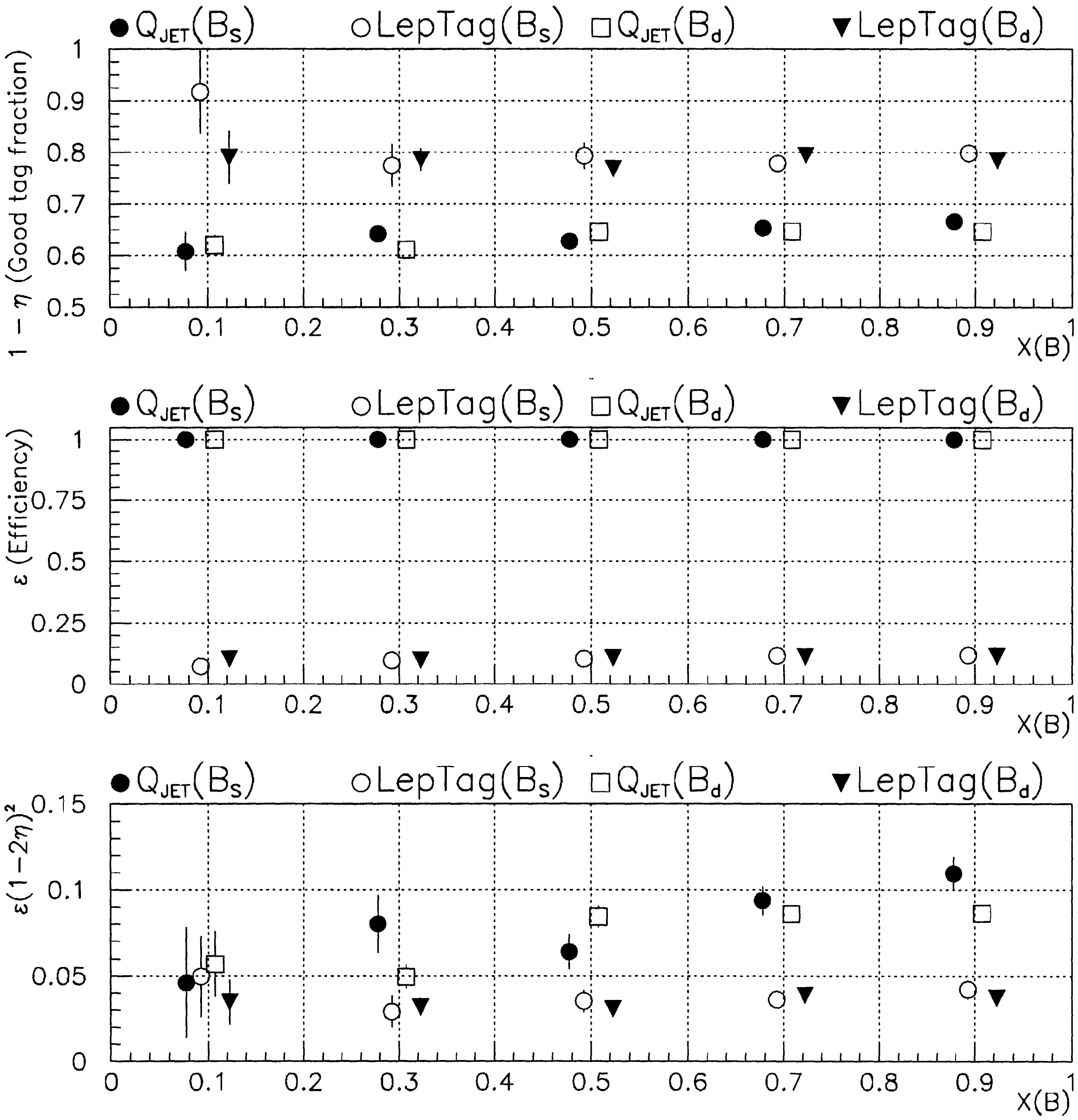

Figure 5: The tagging fraction, efficiency and relative quality factors for B_s^0 – and B_d^0 –tagging using Q_{JET} or a high p_T lepton ($p_T > 1.\text{GeV}/c$) in the opposite hemisphere as a function of X(B). Note the suppressed zeros. The points are offset from the bin centers to make them easier to see.

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[7] Measurement of $\mathrm{B_s^0}$ $\overline{\mathrm{B_s^0}}$ oscillations using semi–leptonic decays, P. Roudeau LAL 90–47

[8] Minutes of the lifetime–mixing meeting of 29-nov-1993.

[9] Inclusive $\pi^\pm$, $K^\pm$ and $p, \overline{p}$ Cross–sections at the Z^0 resonance, Philip Reeves, ALEPH 93-148(PHYSIC 93–128)

[10] The details of this analysis have been presented in [8].

$N(B_s^0)$	F(good) %	ϵ %	ψ %	Tag
1402	78.8(1.1)	11.3(0.3)	3.8(0.3)	LepTag($p_T > 1$ GeV)
1124	81.8(1.7)	9.1(0.3)	3.7(0.3)	LepTag($p_T > 1.25$ GeV)
12362	65.2(0.4)	100.0(0.0)	9.2(0.5)	Q_{JET}(oppo)
7413	66.5(0.5)	59.9(0.4)	6.5(0.4)	K_{TAG}
11248	62.9(0.5)	90.9(0.3)	6.1(0.4)	Fastag
11987	64.8(0.4)	96.9(0.2)	8.5(0.5)	Q_{JET}(same)
11987	65.7(0.4)	96.9(0.2)	9.6(0.5)	Q_{JET}^{F}
11951	66.1(0.4)	96.6(0.2)	10.0(0.5)	$Q_{JET}^{F(NSP)}$
11987	65.4(0.4	96.9(0.2)	9.2(0.5)	$Q_{JET}^{F}(1/3)$
11951	65.4(0.4	96.6(0.2)	9.2(0.5)	$Q_{JET}^{F(NSP)}(1/3)$
11930	60.2(0.4)	96.5(0.2)	4.0(0.4)	Q_{JET}^{π}
11962	63.8(0.4)	96.7(0.2)	7.4(0.5)	Q_{JET}^{K}
11034	60.6(0.5)	89.2(0.3)	4.0(0.4)	Q_{JET}^{p}

Table 1: The number of tagged B_s^0 , $N(B_s^0)$, and the fraction of good tags, efficiencies and relative quality factors (with their statistical uncertainties) for B_s^0 initial state tagging and $X(B) > 0.30$. See text for further details.

$N(B_d^0)$	F(good) %	ϵ %	ψ %	Tag
4552	78.5(0.6)	11.2(0.2)	3.6(0.2)	LepTag $p_T > 1$ GeV
3662	81.1(0.7)	8.9(0.1)	3.4(0.2)	LepTag $p_T > 1.25$ GeV
40737	64.5(0.2)	100.0(0.0)	8.4(0.3)	Q_{JET}(oppo)
23509	56.8(0.3)	57.7(0.2)	1.1(0.1)	K_{TAG}
36985	60.2(0.3)	90.8(0.1)	3.8(0.2)	Fastag
39575	62.9(0.2)	97.1(0.1)	6.5(0.2)	Q_{JET}(same)
39575	61.5(0.2)	97.1(0.1)	5.1(0.2)	Q_{JET}^{F}
39469	61.4(0.2)	96.9(0.1)	5.0(0.2)	$Q_{JET}^{F(NSP)}$
39575	61.4(0.2)	97.1(0.1)	5.1(0.2)	$Q_{JET}^{F}(1/3)$
39467	60.9(0.2)	96.9(0.1)	4.6(0.2)	$Q_{JET}^{F(NSP)}(1/3)$
39450	64.2(0.2)	96.8(0.1)	7.9(0.3)	Q_{JET}^{π}
39508	55.5(0.3)	97.0(0.1)	1.2(0.1)	Q_{JET}^{K}
36238	55.7(0.3)	88.9(0.2)	1.2(0.1)	Q_{JET}^{p}

Table 2: The number of tagged B_d^0 , $N(B_d^0)$, and the fraction of good tags, efficiencies and relative quality factors (with their statistical uncertainties) for B_d^0 initial state tagging and $X(B) > 0.30$. See text for further details.

N(B)	F(good) %	ϵ %	ψ %	Tag
1243	64.6(1.4)	95.2(0.6)	8.1(1.6)	Q_{JET}(same)
835	66.0(1.6)	67.2(1.3)	6.7(1.4)	$K_{TAG}(1)$
835	66.0(1.6)	67.2(1.3)	6.9(1.7)	$K_{TAG}(2)$

Table 3: The number of tagged reconstructed D_s^+, l^- , N(B) and the fraction of good tags, efficiencies and relative quality factors (with their statistical uncertainties) for B_s^0 initial state tagging. See text for further details.